

# A Far Ultraviolet Study of the Old Nova V841 Oph

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## ABSTRACT

We have carried out a synthetic spectral analysis of archival IUE spectra of the old nova V841 Oph (Nova Oph 1848) taken 15 years apart. The spectra reveal a rising continuum shortward of 1560Å, a C IV P-Cygni profile indicative of wind outflow associated with disk accretion in one spectrum, a deep Ly  $\alpha$  profile, and strong N V (1238Å, 1242Å) and O V (1371Å) wind/coronal absorption lines. Numerous sharp interstellar resonance lines are also present. A grid of high gravity atmospheres and accretion disk models, spanning a wide range of inclinations, accretion rates and white dwarf masses was compared to the de-reddened spectra. We find that, for a steady state accretion disk model to account for the FUV spectra, the accretion rate is only  $\sim 3 \times 10^{-11} M_{\odot}/\text{yr}$ , 147 years after its outburst in 1848, with an implied distance within  $\sim 300$  pc. The accretion rate at 147 years post-outburst is smaller than expected for an old nova.

*Subject headings:* stars: old novae – cataclysmic variables – stars: individual (V841 Oph)

## 1. Introduction

Cataclysmic variables are a diverse class of semi-detached, compact, interacting binaries in which a white dwarf (WD) primary star accretes matter from a gaseous disk formed by mass transfer from a Roche lobe-filling main sequence secondary star. The classical novae and recurrent novae are subclasses of CVs whose outbursts are due to explosive thermonuclear burning on the surface of the White dwarf. A typical outburst will produce a maximum increase in brightness of  $\sim 6 - 15$  mag and release  $10^{44} - 10^{46}$  ergs. When taking into account the observed frequency of classical nova outbursts and the observed CV space density, we

can infer a lower limit recurrence time for a given system to be  $\sim 10^4 - 10^5$  yr. Thus the recurrence time is very short compared to the lifetime of a CV so that CVs will experience many classical nova outbursts in their lifetimes. The old novae and recurrent novae are the only CVs that have recorded evidence of having undergone nova explosions.

Among the old novae, DI Lac (Moyer et al. 2003) and V841 Ophiuchi are the only such systems that have optical and UV spectra resembling the UX UMa-type nova-like variables (Warner 1995 and references therein). Emission line widths are very narrow, indicating a low inclination, as first noted by Kraft (1964) and later confirmed by other studies. A low inclination could explain why these two old novae have the highest optical to X-ray flux ratios. We note however, that their optical spectra are quite different (Hoard et al. 2000). The optical spectra of DI Lac reveal broad, shallow Balmer and helium absorption lines with superimposed weak emission lines, whereas V841 Oph reveals strong single-peaked Balmer, He I and He II emission features.

The impetus for this work arises from the paucity of knowledge about the white dwarfs and accretion disks in old novae. How high are their accretion rates in the post-nova state? Is there a correlation between the time since the nova and the accretion rate in the old nova system? How quickly is an accretion disk established following a nova explosion? How hot is the post-nova white dwarf and how was it affected by the explosion? These basic questions lack definitive answers and underscore the need for advancing our knowledge of these systems. This is especially true in the FUV range as shown in the recent analysis of the HST STIS spectrum of DI Lac (Moyer et al. 2003).

V841 Oph was discovered at the time of its outburst in 1848, as Nova Oph 1848 and the early literature classified it as a fast nova. However, the true maximum was very likely missed and hence the correct  $t_3$  value remains uncertain. This uncertainty in  $t_3$  and its impact on the speed class and distance estimates of V841 Oph is discussed in section 3.1 below. Its orbital period is  $0.60144 \pm 0.00056$  (Ritter and Kolb 1998). The observed or estimated physical and orbital parameters published for V841 Oph are listed in Table 1.

Warner (1995) derives absolute magnitudes of CV subtypes and assigned  $M_V = +3.9$  as an average for old novae as a class which, if due to accretion, implies an accretion rate of  $10^{-8} M_\odot/\text{yr}$ . Warner found a strong correlation between emission line equivalent widths and the inclinations of the CV systems, as well as a strong correlation between the inclination angle and the absolute magnitude. The systems having higher inclination angles also had lower  $M_V$  values than those that had smaller inclination angles. Moreover, the systems that were nearly pole-on, like DI Lac and V841 Oph, were found to have the highest  $M_V$  values.

## 2. Far Ultraviolet Archival Observations

We extracted the archival spectra of V841 Oph from the IUE NEWSIPS final archive. The observing log is given in Table 2 where we have listed, by column: SWP image number, exposure time, starting time of the exposure, the original program ID and the continuum and background counts. The observations were made using the large aperture with the short-wavelength prime camera (SWP) at low dispersion with a resolution of 5Å, covering a wavelength range of 1170-2000Å.

We carried out a flux calibration/correction to the IUE NEWSIPS spectra using the Massa-Fitzpatrick correction algorithm to improve data quality and signal-to-noise. Massa & Fitzpatrick (2000) showed that the NEWSIPS low-dispersion data had an absolute flux calibration that was inconsistent with its own reference model and also subject to time-dependent systematic effects which could, added together, amount to 10-15%. Using our corrected fluxes, we removed the effect of interstellar reddening by using the IDL routine UNRED with  $E(B-V) = 0.50$  (Verbunt 1997).

The two spectra for V841 Oph were taken just over 15 years apart. However, they are remarkably different from each other. The first spectrum has a better signal-to-noise and a possible P Cygni profile in C IV 1550Å. The more recent spectrum seems to have no discernable wind outflow, yet also has flux levels marginally higher than the earlier spectrum. It lacks a distinguishable P Cygni profile, and is generally noisier than the earlier spectrum. The lower quality of the second spectrum is due largely to the degradation of the SWP camera which marked the last few years of IUE operations.

Despite the noise level in both spectra, a few strong line features are unambiguously identifiable. The strongest features in SWP07950 are the broad Ly  $\alpha$  absorption, the aforementioned C IV (1550Å) absorption, N V (1240Å) absorption and Si III + O I (1300Å) absorption are also evident. The peak to peak noise level in SWP54455 preclude a clear identification of any line feature other than the Ly  $\alpha$  absorption, likely Si III + O I (1300Å) absorption, and N V (1240Å) absorption. In both spectra, there is a hint of Si IV (1260Å) absorption. However, it is somewhat puzzling that Si II (1260Å) is weak, if present at all, relative to the prediction of a solar composition accretion disk (see below). This would suggest the possibility that Si is underabundant relative to solar composition. This is also suggested by the absence of Si IV wind absorption in the face of C IV (1550) and N V (1240Å), all three of which are typically seen together in cataclysmic variable wind outflows. A similar underabundance of Si was seen in the analysis of the HST STIS spectrum of DI Lac (Moyer et al. 2003).

### 3. Synthetic Spectral Modeling

The TLUSTY (Hubeny 1988) and SYNSPEC (Hubeny & Lanz 1995) codes were used to create model spectra of white dwarf stellar atmospheres. Solar abundances were assumed. Wade & Hubeny's (1998) optically thick disk model grid was the source of model accretion disks. We then used IUEFIT, which is a  $\chi^2$  minimization routine, to calculate a  $\chi^2$  value and a scale factor for each of our models.

The scale factor S is defined in terms of the stellar radius R and distance  $d$  by:

$$F(\lambda_{obs}) = S H(\lambda_{model})$$

$$\text{where } S = 4(\pi)(R^2/d^2).$$

The scale factor is normalized to one kiloparsec for the distance and one solar radius for the radius. Thus, for a photosphere the distance  $d$  is given by:

$$d = 1000\text{pc} (R_{wd}/R_\odot)/ S^{0.5}.$$

Since the accretion disk model fluxes are normalized to a distance of 100 pc, for an accretion disk fit, the distance is given by:

$$d = 100/S^{0.5}\text{pc}.$$

We also carried out combination fits utilizing both the best-fitting accretion disk model and the best-fitting photosphere model. With this fit, we were able to obtain the relative contributions of the accretion disk and the white dwarf.

The spectra were prepared for fitting by masking regions with negative flux. For SWP54454 we masked 1190-1223Å, along with 1787-1793Å. For SWP07950 we masked wavelengths  $< 1228\text{\AA}$ , as well as 1925-1927Å.

First, we carried out accretion disk-only fits to the data. We ran models with white dwarf masses of 0.350, 0.550, 0.800, 1.030 and 1.210 solar masses. There was also a range of  $\log \dot{M}$  values from -8.0 up to -10.5 in increments of 0.5. The disk inclination angle  $i$  was kept fixed at  $18^\circ$  in all of the fits to be consistent with the evidence that V841 Oph is a very low inclination system. The parameters of the best-fitting accretion disk models are summarized in Table 3. For the same white dwarf mass of  $0.8 M_\odot$ , the best-fitting disk-only model to SWP07950 is displayed in fig. 1 while the best-fitting disk model to SWP54454 is displayed in fig. 2. For a fixed white dwarf mass of  $1.0 M_\odot$ , the best-fitting disk-only models to SWP07950 and SWP54454 are displayed in figs. 3 and 4, respectively. The best-fitting accretion disk models to both spectra have the same accretion rate,  $\sim 3 \times 10^{-11} M_\odot/\text{yr}$ , and the scale factors of these best-fits place V841 Oph within 200 pc of the sun.

It is noteworthy that in both spectra, relative to the disk model fits, the data show a broad “bump” centered at  $\sim 1500\text{\AA}$  unaccounted for by the model disk continuum. While this “bump” could be due to underlying emission giving the appearance of a curved continuum in that region, we believe that another possibility is more likely, namely that there is an underlying high velocity component (an accretion belt on the white dwarf or an optically thick inner disk/boundary layer ring in which the Keplerian broadening of the wings of smeared absorption lines produces the “arched” continuum in that region.) We have seen this in VW Hydri’s white dwarf spectrum during quiescence and regard it as a hallmark of such an underlying high velocity component. If this is the case, then in V841 Oph, the curvature of the continuum could be due to the merging of Keplerian-broadened wings.

Next, we applied white dwarf photosphere models. We found that our best-fitting models to the two spectra were achieved with a temperature of 18,000K-20,000K and  $\log g = 8$ . For comparison with the disk fits, we display the best-fitting photosphere model to SWP54454 in fig. 4 and the best-fitting photosphere model to SWP07950 in fig. 5.

We also combined the best-fitting white dwarf photosphere fluxes with the best-fitting accretion disks fluxes, varying the disk fluxes by a small increment between 0.1 and 10 until a best combination fit was achieved (see Winter and Sion (2003) for the details of this technique). The resulting best-fitting photosphere plus disk fit to the two spectra yielded distances of 260 pc for SWP07950, and 258 pc for SWP54454, which are both close to the more recently published values by Warner (1987). Combined models showed an overwhelming contribution from the disk itself, with 94% of the SWP07950 flux, and 94% of the SWP54454 flux coming from the accretion disk.

Although we fixed the inclination of V841 Oph at  $18^\circ$  and adopted  $0.8 M_\odot$  and  $1.0 M_\odot$  as the most likely white dwarf masses in our accretion disk model, we extended our fits to encompass the range of probable white dwarf masses and orbital inclinations derived by Diaz and Ribeiro (2003) based upon probability calculations in their radial velocity study. If we adopt an inclination as high as  $60^\circ$ , then for a white dwarf mass of  $0.8 M_\odot$ , we find that the best-fitting accretion disk model has an accretion rate of  $3 \times 10^{-10} M_\odot/\text{yr}$  and a scale factor-derived distance of 283 pc. If we adopt a white dwarf mass of  $0.35 M_\odot$ , which lies close to the lower end of the Diaz and Ribeiro (2003) mass range, then we obtain a best-fitting disk model with an accretion rate of  $1 \times 10^{-9} M_\odot/\text{yr}$  and a model-derived distance of 229 pc. While we believe that a white dwarf mass this small would imply a helium-rich core, low ejection velocities and extremely long nova recurrence timescales, recent hydrodynamic simulations of classical novae extended to lower white dwarf masses and very low accretion rates do indeed result in nova events (Yaron et al. 2005). In the final analysis, all of our accretion disk model fits imply that the distance to V841 Oph is below 300 pc.

### 3.1. The Distance to V841 Oph

The distance implied by our model fitting is considerably closer than one typically associates with old novae. In fact, classical novae are often found at larger distances than other CV types at least in part because they are discovered during their bright outbursts (i.e., it is influenced by an observational selection effect). In view of the cyclical (hibernation) evolution scenario for CVs, it should not be surprising to find novae at distances comparable to a “typical” CV (i.e., a few hundred pc). Given that V841 Oph is located in the direction of the Galactic bulge where novae typically are at larger distances, the distance we have derived for V841 Oph would be puzzling. However, it cannot be ruled out that V841 Oph is simply a disk object that lies between the sun and the center of the Galaxy.

The early literature classified V841 Oph as a fast nova. If the true maximum was missed, then the nova was brighter and the parameter  $t_3$  smaller. A smaller  $t_3$  indicates an intrinsically brighter nova. Payne-Gaposchkin (1957) pointed out the difficulty of reducing the different observations to a consistent light curve and that the true maximum, which she thought was near +2, was missed. After combining this information with that of Pickering (1900), based on observations by F.W.A. Argelander, the first observation of a magnitude of +5.0 is 9 days later than Payne-Gaposchkin’s approximate maximum. If the Pickering magnitudes are reliable, this suggests a  $t_3$  value of about 12 days. Using the magnitude-rate of decline relationship (Downes and Duerbeck, 2000) for a light curve of type B (Duerbeck, 1981), leads to an absolute magnitude of -7.5. The fast nova relationship leads to an absolute magnitude of -9.6. An absorption in V of 1.60 (Gilmozzi et al. 1994) from fitting the UV continuum, then gives corresponding distances of 380 and 1000 pc, respectively. The lower value is closer to our determination of 190 pc. On the other hand, Sherrington and Jameson (1983), by fitting the infrared to include the contribution of the cool component, find a distance between 336 and 301 pc.

Since the true speed class of V841 Oph is uncertain due to different estimates of  $t_3$ , it is worth exploring a slow nova relationship for maximum magnitude (Woronow-Weljaminev 1953; Duerbeck 1981). In this case, the implied distance is  $> 370$  pc for a  $t_3$  value of 23 days. Duerbeck (1987) gives an apparent maximum of +4.2 and a  $t_3$  value of 130 days. For the same interstellar absorption, the corresponding Downes and Duerbeck (2000) relation gives an absolute magnitude of -6.9. The distance then is 790 pc. Warner (1987) gives an absolute magnitude at maximum of -6.5 for a maximum apparent magnitude of +4. His absorption is  $A_v = 1.25$  and the distance obtained is 710 pc. Gilmozzi et al (1994) compiled various sources of maximum magnitude-rate of decline relationships and  $t_3$  obtaining a distance of 680 pc. We have summarized the various estimates of  $t_3$ , speed class and distances in Table 4.

What do we make of all of this? Certainly the correct empirically-determined distance to V841 Oph remains unclear. While old novae tend to be much more distant than what we have derived for it, there are old novae which are comparably as close, those being V603 Aql (238 pc from a Hipparcos parallax), DQ Her (327 pc), and HR Del (285 pc), the latter two from Warner (1987). We are encouraged that our model-derived distance is close to the distance range estimated by Sherrington and Jameson (1983). Our distance for V841 Oph is also reinforced by the HST STIS study of the old nova DI Lac (Moyer et al. 2003) which is almost a spectroscopic twin of V841 Oph. While the accretion rate is higher in DI Lac (Nova Lac 1910) by a factor of 10 to 30 compared with V841 Oph (Moyer et al. 2003), the distance implied by the scale factor of the best-fitting accretion disk models in that study (after correcting a normalization error) are in the range of 199 to 292 pc. If our model-derived distance is incorrect, then there may be something wrong with using steady state accretion disk models for old novae like V841 Oph and DI Lac or there are missing pieces of physics in the accretion disk models we have used.

#### 4. Summary

The two spectra of V841 Oph, taken 15 years apart, reveal a difference in flux level with the later one having a higher flux level but no evident P Cygni profile structure. The latter could be due to orbital phase-dependent changes in the profile structure rather than a shutdown of the outflow. Our synthetic spectral analysis of V841 Oph with model accretion disks and photospheres reveals that the FUV spectrum is completely dominated by an optically thick, steady state disk. This is no surprise. However, since previous observational evidence supports a low inclination and high intrinsic luminosity for the system, it is surprising that the best-fitting steady state accretion disk implies an accretion rate of  $\sim 3 \times 10^{-11}$   $M_{\odot}/\text{yr}$ . This is at least two orders of magnitude lower than the accretion rate one typically associates with old novae based upon their average absolute magnitudes, and lower than the typical accretion rates derived for nova-like variables such as IX Vel and RW Sex. While the nova-like variables have had no recorded outburst, the IUE spectra of V841 Oph and DI Lac were observed 132 years and 76 years after their classical nova explosions. Therefore, if our accretion rates are correct, then their post-nova accretion rates, roughly a century after their nova episodes, have declined significantly to levels below the rates associated with the high states of VY Scl-type nova-like variables. ( $> 1 \text{ kpc}$ ).

It is clear that further FUV spectroscopic observations and distance determinations from parallaxes are needed to confirm the results suggested by our archival study.

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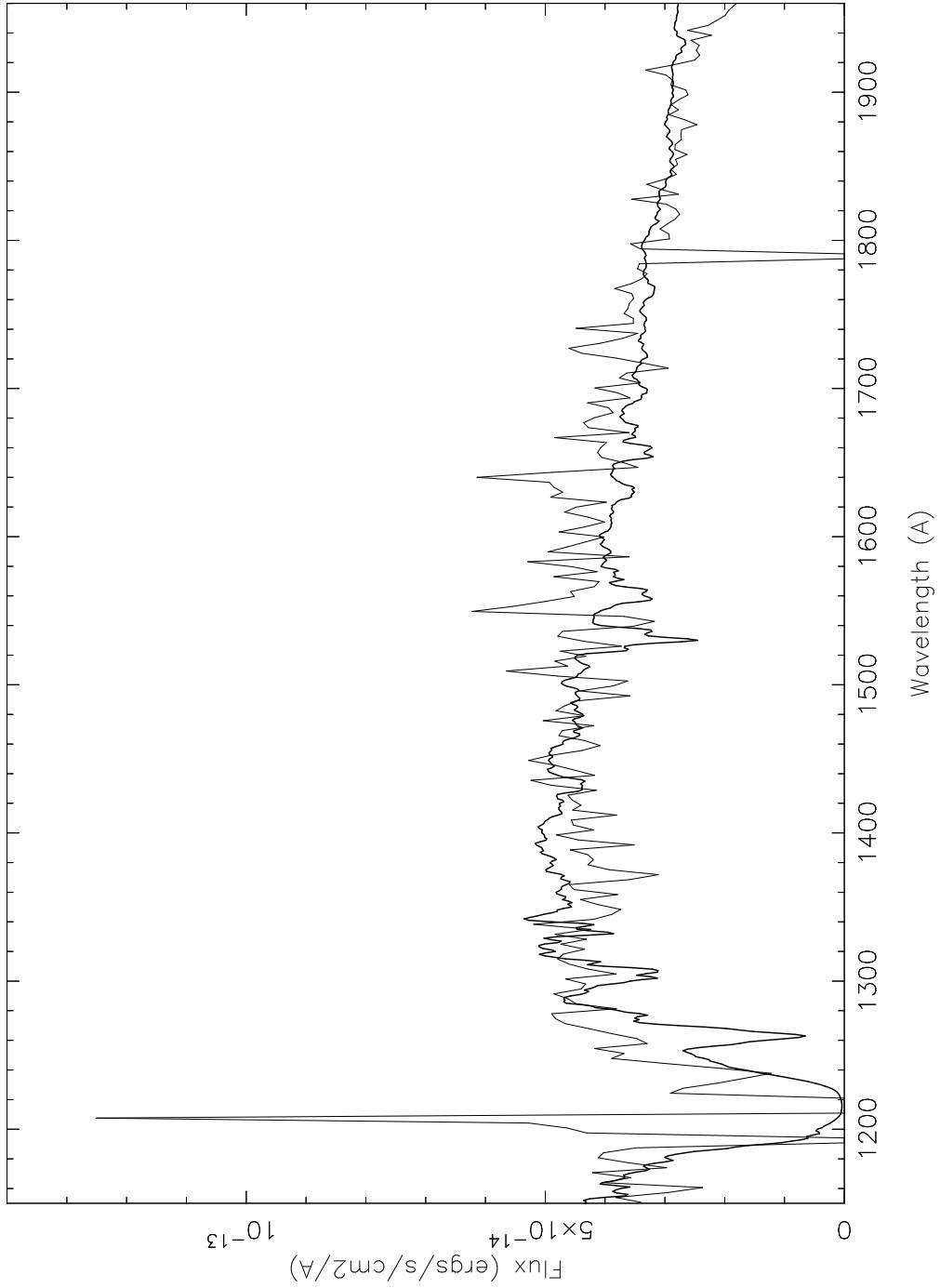


Fig. 1.— Plot of Flux  $f_\lambda$  (ergs/s/cm<sup>2</sup>/Å) versus wavelength (Å) for IUE spectrum SWP07950 shown with the best-fit accretion disk model with  $\dot{M} = 10^{-10.5} M_\odot/\text{yr}$ ,  $i = 18^\circ$  and  $M_{wd} = 0.80 M_\odot$ .

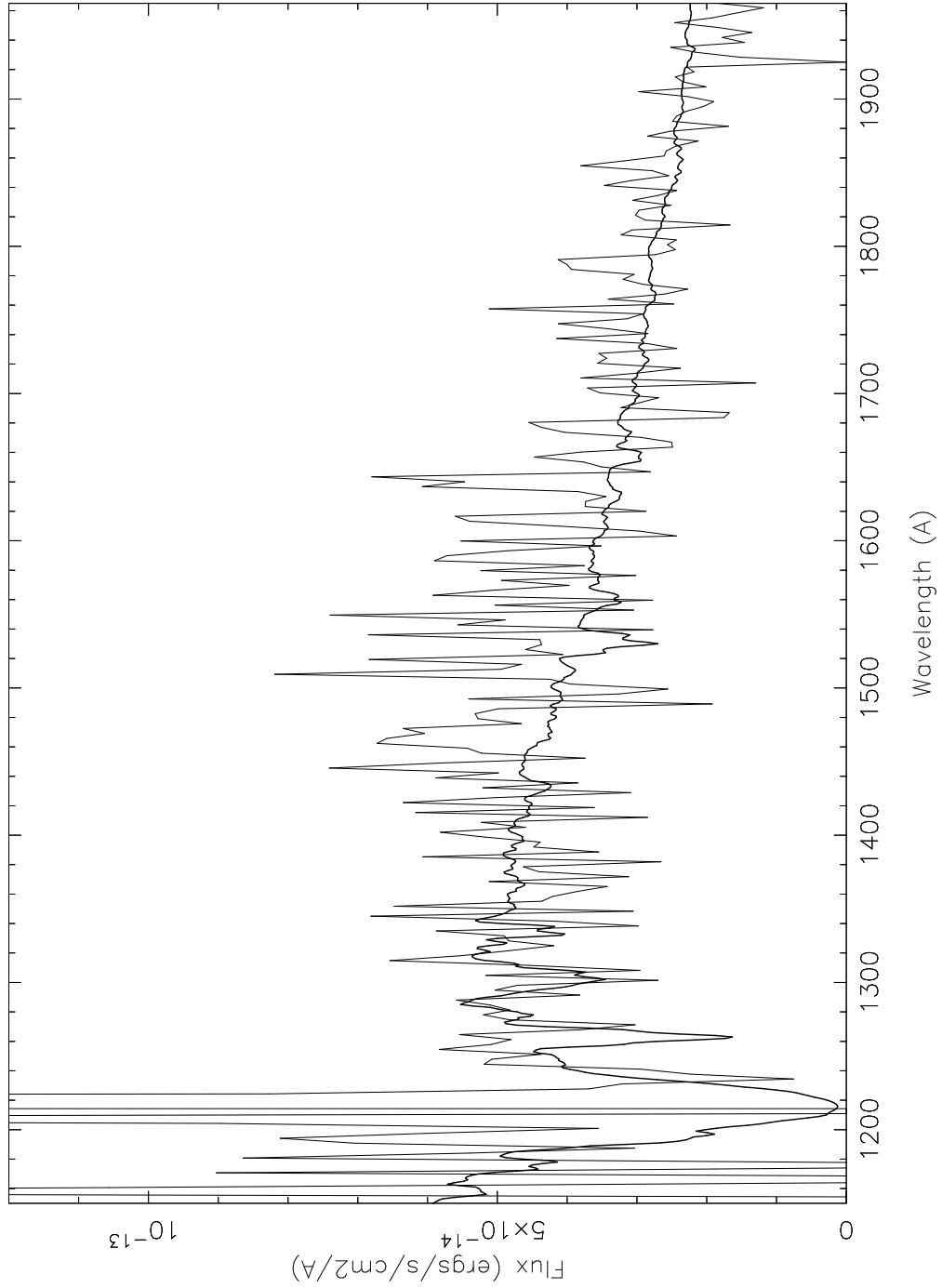


Fig. 2.— Plot of Flux  $f_\lambda$  (ergs/s/cm<sup>2</sup>/Å) versus wavelength (Å) for IUE spectrum SWP54454 shown with the best-fit accretion disk model with  $\dot{M} = 10^{-10.5} M_\odot/\text{yr}$ ,  $i = 18^\circ$  and  $M_{wd} = 0.80 M_\odot$ .

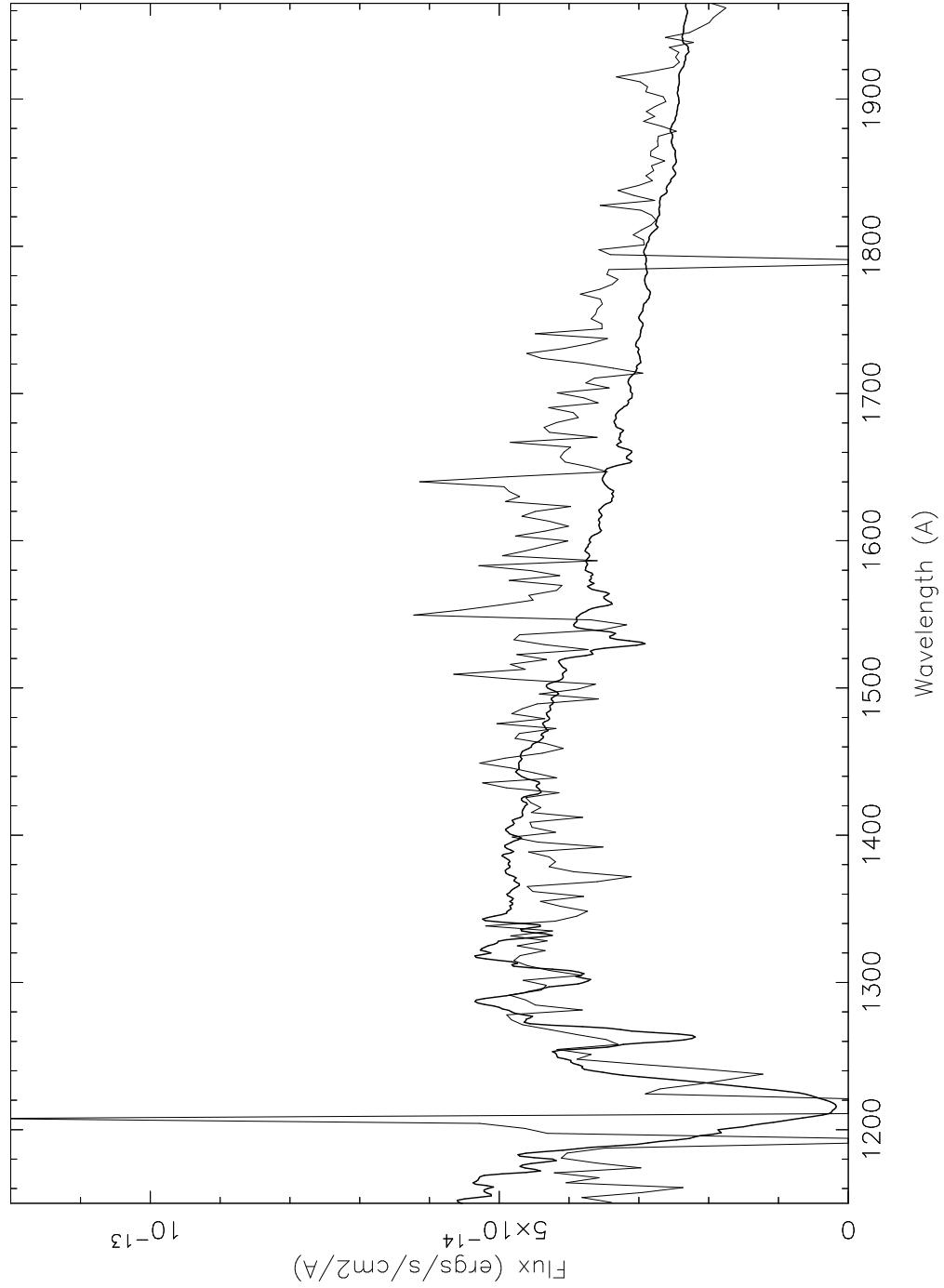


Fig. 3.— Plot of Flux  $f_\lambda$  (ergs/s/cm<sup>2</sup>/Å) versus wavelength (Å) for IUE spectrum SWP07950 shown with the best-fit accretion disk model with  $\dot{M} = 10^{-10.5} M_\odot/\text{yr}$ ,  $i = 18^\circ$  and  $M_{wd} = 1.0 M_\odot$ .

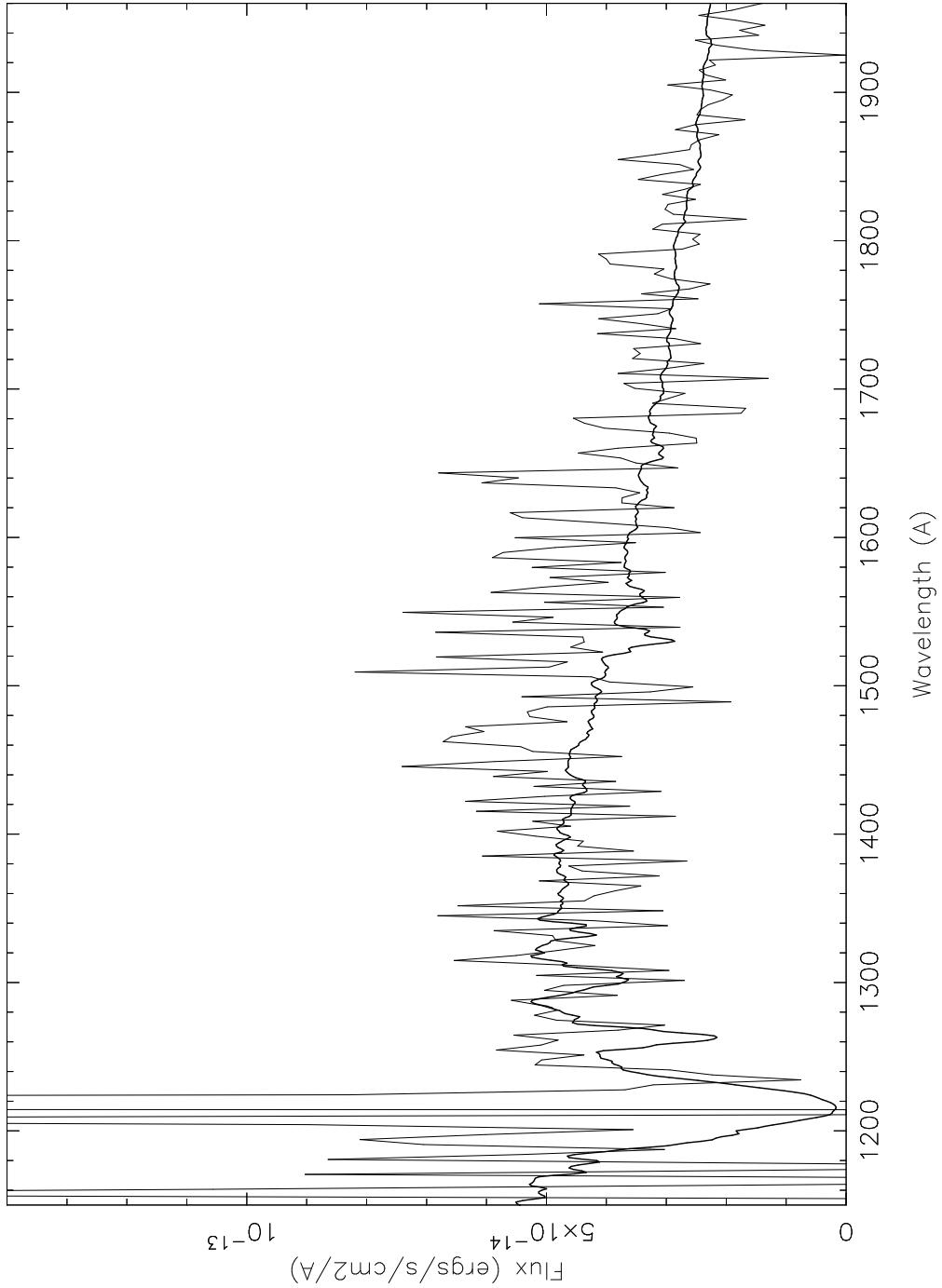


Fig. 4.— Plot of Flux  $f_\lambda$  (ergs/s/cm<sup>2</sup>/Å) versus wavelength (Å) for IUE spectrum SWP54454 shown with the best-fit accretion disk model with  $\dot{M} = 10^{-10.5} M_\odot/\text{yr}$ ,  $i = 18^\circ$  and  $M_{wd} = 1.0 M_\odot$ .

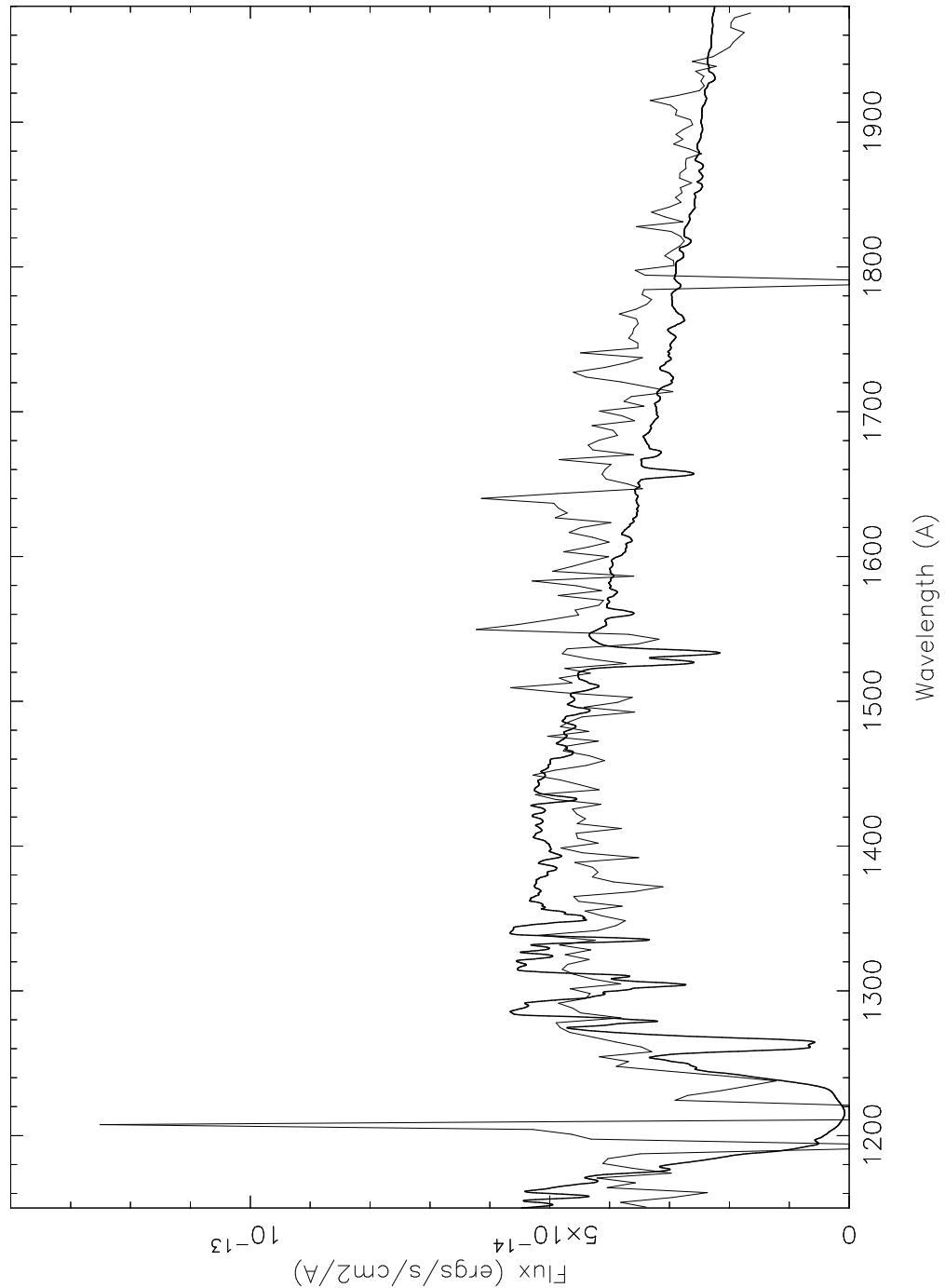


Fig. 5.— Plot of Flux  $f_\lambda$  (ergs/s/cm<sup>2</sup>/Å) versus wavelength (Å) for IUE spectrum SWP54454 shown with the best-fitting high gravity ( $\log g = 8$ ) model with  $T_{eff} = 18,000$  K.

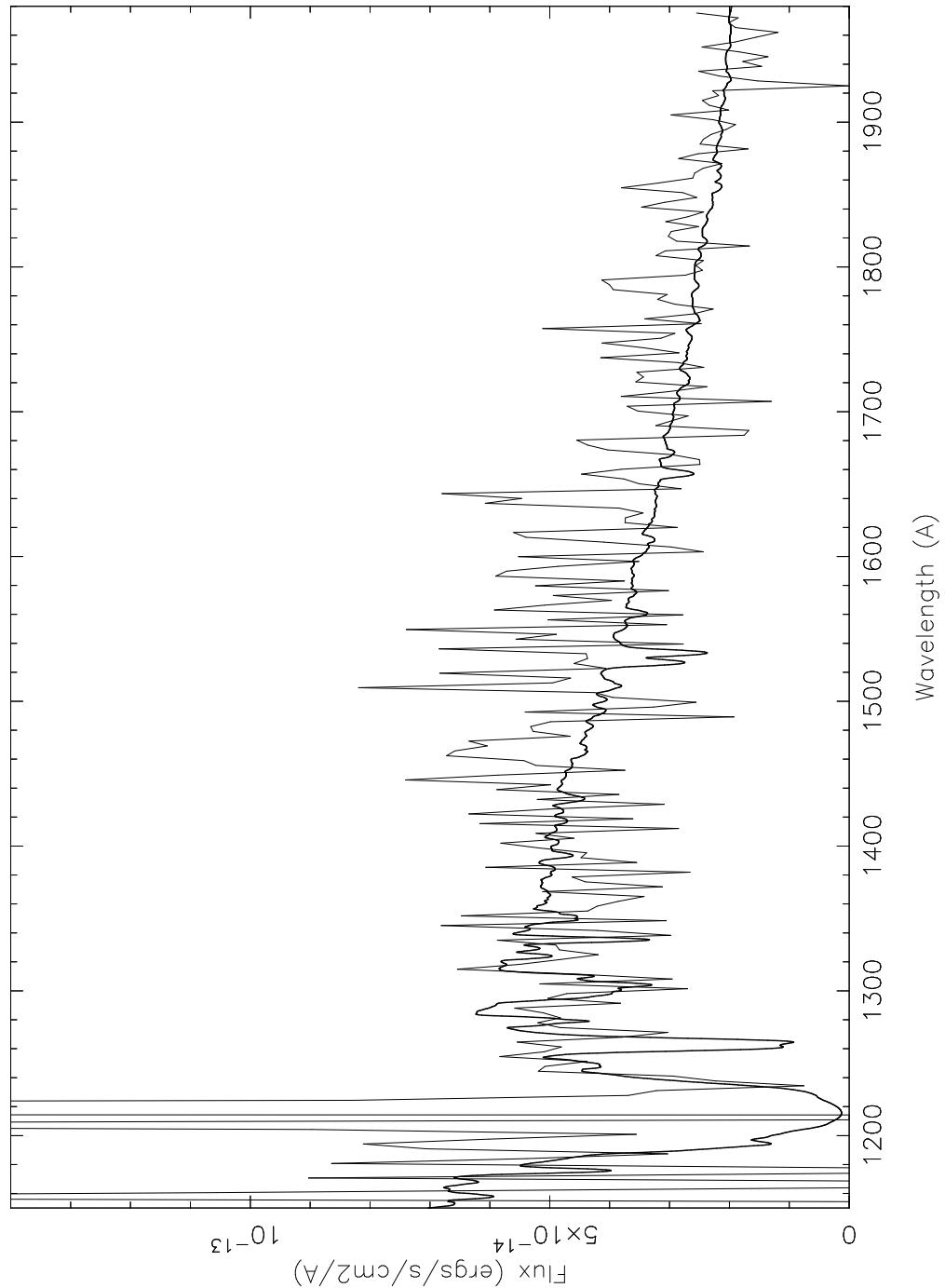


Fig. 6.— Plot of Flux  $f_\lambda$  (ergs/s/cm $^2$ /Å) versus wavelength (Å) for IUE spectrum SWP07950 shown with the best-fitting high gravity ( $\log g = 8$ ) model with  $T_{eff} = 20,000$  K.

Table 1. PARAMETERS OF V841 OPH

system	V841 Oph
log P [days]	-0.219 <sup>a</sup>
$i[^{\circ}]$	$\sim 0^b$
$M_V^*$	3.9
$M_{WD}$	1?
$\log \dot{M}$	-8.03

References. — (a)  
Hoard et al. 2002;(b)  
Warner (1995)  
\* Corrected for inclination  
effects

Table 2. IUE OBSERVING LOG

Data	$t_{exp}$	Dispersion	Aperture	Date of Exposure	Cont. Cts	Back. Cts
SWP54454	3600	LOW	LARGE	1995-04-17 19:41:00	122	77
SWP07950	7200	LOW	LARGE	1980-02-14 20:54:00	92	34

Table 3. ACCRETION DISK FITTING PARAMETERS

Parameter	SWP54454	SWP07950
$M_{WD}(M_\odot)$	0.8	1.0
$i^\circ$	18	18
$\dot{M}(M_\odot/\text{yr})$	-10.5	-10.5
$\chi^2$	1.49179	2.48270
S	0.712911	0.266539
$d$	188	194

Table 4. V841 OPH DISTANCE ESTIMATES

Source	$t_3$ (d)	$d$ (pc)
Downes and Duerbeck (2000)	~12	380 (Type B Light Curve)
Fast Nova $t_3$ Relationship	~12	1000
Sherrington and Jameson (1983)	–	301–336
Slow Nova $t_3$ Relationship	23	>370
Duerbeck (1981)	130	790
Warner (1987)	–	710
Gilmozzi et al (1994)	–	680